INVENTIVE PERFORMANCE IMPROVEMENT
OF
INTEGRATED OPTICAL RATE SENSOR
USING I PS/TRIZ

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ABSTRACT

The Theory of Inventive Problem Solving (TIPS or also known as TRIZ) is a new scientific approach to innovative improvements of products and processes. This methodology was applied to inventively improve performance of an Integrated Optic Rate Sensor (IORS). The problem was to improve angular rate sensitivity, but light is lost due to the need for an increased optical waveguide length. In other words, there are sound technical reasons to have the length of the waveguide both long and short. Development of new innovative ideas was based on the understanding of the "Laws of Engineering System Evolution", "Inventive Principles" and "Effects" applied to solve this physical contradiction. Using the "Inventive Machine Expert System Software," sixty-four potential new solutions were generated in a very short time. The number of new solutions generated by using TRIZ is considered to be over an order of magnitude higher than using the old methods. Two ideas have patent level quality.

I. Introduction

"Innovate or disappear" is the slogan often heard today. In the last two hundred years, the quality of life on earth was tremendously improved due to millions of inventions and innovations world wide in the field of engineering and technology. Invention and innovation are born as the necessity to solve a new technical or nontechnical problem. As customers demand for better and better quality products is ever increasing, so is the demand for innovative products and process.

The Theory for Inventive Problem Solving (TIPS), also known as TRIZ after its Russian acronyms, is a newly U.S. introduced methodology that is revolutionizing the way the problem solving is performed. This new concept was first conceptualized in 1946 by Dr. Genrich S. Altshuller, a brilliant Russian inventor. The concept was further extended and used by thousands of engineers all over former Soviet Union at 11. I more recently adopted by engineers and inventors in Europe, Japan, Israel and U.S.

The Integrated Optic Rate Sensor (IORS) was chosen to inventively improve its performance by applying the principals of TIPS/TRIZ. The task of applying this new methodology was tremendously facilitated by using the three expert system applications provided by Inventive Machine Corporation that combines artificial intelligence with the Altshuller's TRIZ theory. All three currently available Inventive Machine Expert System software packages were used: Inventive Machine Principles (I M-I)); Inventive Machine Predictions (IM-Pr); and Inventive h4ac.hint Effects (IM-E). The main goal was to provide the opportunity to apply these powerful inventive concepts and use the highest possible concentration of necessary knowledge in order to solve the IORS improvement problem. The problem was to improve the IORS angular rate sensitivity while light was lost in a longer optical waveguide that is required in order to improve angular rate sensitivity. Using TRIZ defined "Laws of Engineering System Involution", "Inventive Principles", and "Effects", a large number of possible new inventive solutions were generated in a very short time.

II. Technical Description

Integrated Optic Rate Sensor (IORS) is a micro optical waveguide on a rectangular silicon wafer. The optical waveguide is sputtered glass on silicon wafer utilizing an e-beam formed mask for waveguide fabrication. Figure 1 and 2 provide top and side views of the IORS.

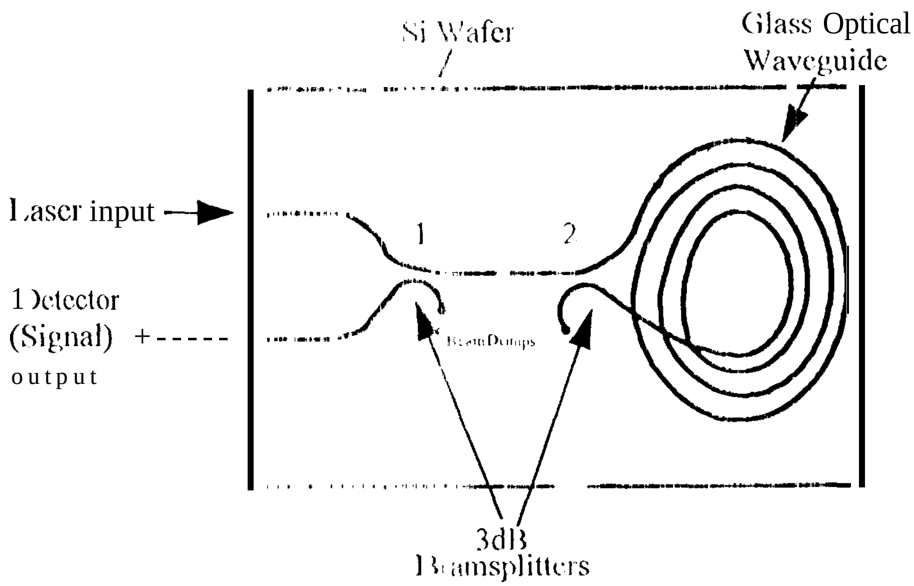
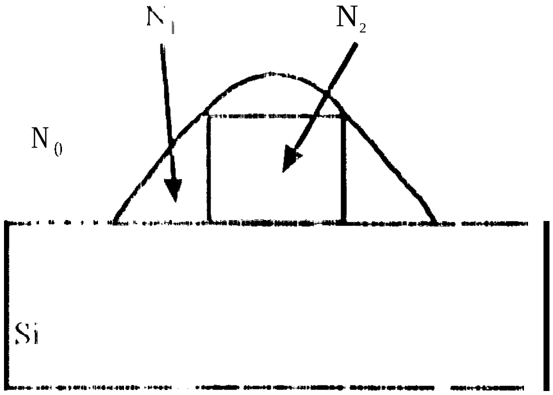


Figure 1. IORS Top View



Where:

Index of Refraction

$N_0 < N_1 < N_2$

Figure 2 IORS Side View

III. Principals of Operation

Laser light is coupled into optical waveguide and propagates to beamsplitter 2. (See figure 1.) Beamsplitter 2 splits the light equally, thus two beams propagate in opposite directions in the spiral waveguide. Counter-propagating light recombines at beamsplitter 2 and propagates to beamsplitter 1. Beamsplitter 1 splits the light equally; one-half the light returns to the optical source input (unfortunately) and one-half is coupled to the photodetector. The device measures rate of rotation utilizing the "Sagnac effect", where the rotation rate input axis is perpendicular to the plane of the spiral waveguide.

Normally, counter propagating light beams in the spiral waveguide recombine at beamsplitter 2, in phase. At a rotation rate input Ω, the counter propagating light beams in the spiral waveguide recombine at beamsplitter 2, out of phase.

Where delta phase, $\Delta\Phi = \frac{4\pi L R \Omega}{\lambda c}$

- L = Length of Spiral Waveguide
- R = Mean Radius of Spiral Waveguide
- λ = Wavelength of Light
- c = Speed of Light
- Ω = Input Rotation Rate

IV. Technical Problem to be Solved.

Since rotation rate sensitivity is proportional to length of the waveguide, we would like to make the optical path length of the spiral waveguide as long as possible. Unfortunately, the losses in the optical waveguide are large, 0.2 dB/cm. If the losses are too large, no light carrying output signal is detected, and thus no angular rate can be measured. Losses are believed to be due to waveguide roughness.

v. Conflicting 1 ;nvironment

i n order to successfully improve IORS pei formance, several conflicting elements or problems have been identi fied th.itneed to be resolved.

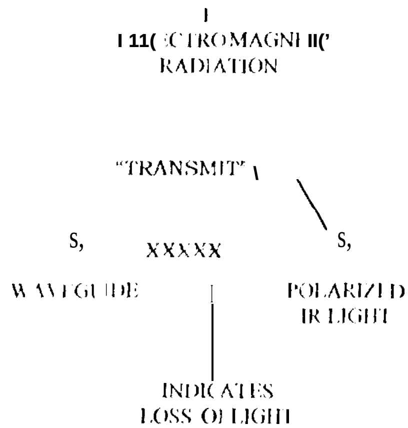
- Management confl ict This IORS technology to be competitive has to be kept at low production cost, low mass an.d s1 11:11 device volume. In order to keep production cost competitive, the intent is to mass produce this miniaturized angular rate sensor. But before it is mass produced, 111. IORS has 10 have high rotation rate sensitive.
- Technical con flict. Low cost low weight, small volume and high rate sensitive IORS is a new un-proven technology. It has been shown that a short optical waveguide has little light loss, but i)er formed at a reduced angular rate. sensitivity. On the other hand, a longer optical waveguide his an improved angular rate sensing, but has large light 1o sscs. Due to optical losses in a longer optical waveguide, a weaker optical signal is detected at the output and thus it is more difficult to measure the angular rate, and therefore no improvement of IORS rate sensitivity is possible.
- Physical conflict. In theory, physical contradiction is when a requirement has opposite parameter characteristics. In the IORS case, the physical conflict is caused by the need to have a short waveguide which is not losing. propagating light but is not rate sensitive , and the need to have a longer waveguide to improve the angular rate sensitivity but is loosing propagating light. The physical contradiction then is: **TO HAVE A SHORT OP TICA L WAVEGUI DE and TO HAVE A LONG OPTICAL WAVEGUIDE**. By el iminating this physical contradiction, the IORS angular rate sensitivity will be improved and the problem will be solved.

V]. Object/Field Investigation

The Object/Field Analysis is t i ie corne stone of TRIZ. Each problem has to be broken down into elements of two objects and a field both for positive response and negative response. The object field analy sis is made up of the following S-Field diagram:

S,- “S,

Where S_2 is a “tool” that acts on “object” S1, and is a “field” that represents an energy source related to the S1 - S2 interaction.
In the 10RS real situation], due to the roughness of the waveguide, some of the polarized input light is lost due to refraction. ‘1 o i mprove the inward propagation by reflection and diminish outward refract ion, a clad is added on the outside of the waveguide. 1 ;ven with the clad added, some polarized input lig htis still lost. The S-Field diagram for our 10RS system is:



The "function" is transmission, or simply TRANSMIT", which is the action-verb in the functional statement, "WAVI :GUII)E TRANSMITS IR LIGHT" The "stars" indicate an undesirable effect, i.e., not all the I R 1 .IGHT i. transmitted; some 1 R LIGHT is lost. The object of the conceptual approach is to have transmission without losses.

VII. The Idealized Function

The ideal situation is when the product is performing at infinite reliability, and at no cost to produce the product,

In an ideal IORS system , the light should propagate through the waveguide as if no waveguide is there at all. The ideal situation is when all returning light is detected at the output regardless of the length of the waveguide. This will allow the rate sensitivity to approach infinity.

VIII. Analysis of 10RS Using Invention Machine Principles Expert System

Using Invention Machine Principles (i M 1'} Expert System, the following Inventive Principles were recommended by the technical contradictions which emerged. These inventive principles were used by analogy, along with the associated patent collection, to arrive at possible solutions to the general problem of "no or little detection signal due to lossses" along the waveguide. Using inventive principals from IM-P software, certain technical conflicts (shown bellow) can be overcome.

Technical Conflict	Recommended Inventive Principle
Length of Stationary Object versus Illumination Intensity	#3 LOCAL QUALITY #25 SELF-SERVICE
Length of Stationary Object versus Losses of information	#24 INTERMEDIARY #26 COPYING
Length of Stationary Object versus Measurement Accuracy	#32 CHANGE OF COLOR #28 CHANGE MECH. DESIGN #3 LOCAL, QUALITY
Length of Stationary Object versus Difficulty of Measurement	#26 COPYING

The principles are defined below.

LOCAL QUALITY:	(1) Go from a UNIFORM STRUCTURE of the waveguide to a NON UNIFORM STRUCTURE; (2) Go from a UNIFORM STRUCTURE of the external environment (light??) to a NON UNIFORM STRUCTURE.
COPYING:	(1) Instead of an unavailable, complicated, expensive, inconvenient or fragile object, use its simpler and cheaper copies; (2) Replace the object or system of objects with optical copies (images), scaling, up or down these copies: (3) If visible optical copies are used, go to infrared or ultraviolet copies.
INTERMEDIARY:	(1) Use an intermediate carrier article (waveguide??); (2) Merge the waveguide temporarily with another object (???) which can be easily removed.
CHANGE OF COLOR:	(1) Change the color of the object or of the external environment; (2) Change the transparency of the object or of the external environment.
SELF-SERVICE:	(1) The object must serve itself by performing auxiliary and repair operations; (2) Use waste (of energy, substance, de.)
CHANGE MECHANICAL DESIGN:	(1) Replace mechanical circuits with optical, acoustical or odor circuits; (2) Use electricity, magnetic or electro-magnetic fields to interact with the object; (3) (h) from static fields to movable ones, from fixed to variable, from non-structured fields to those having a certain structure; (4) Use fields in conjunction with ferro-magnetic particles.

The following observations, recommendations directions, solutions and paths arc observations from applying these inventive principles to the IORS System.

LOCAL QUALITY PRINCIPLE #3

1. Using Local Quality Principle, go from a uniform to a non-uniform structure for the light input, using several laser beams of differing wavelengths, obtaining a wavelength-versus-phase-shift profile which is related to rotational speed (as compared with just one phase shift for onc laser beam, as related to rotational speed).
2. Go from a uniform to a non-uniform waveguide structure. For example, what would the idea of ''many parallel waveguides'' mean?
3. What would a very very small waveguide size mean (and do)?
4. What if the mean radius of the spiral waveguide approached infinity? What would that do, and could it be made?

5. Can wc intentionally usc internal reflection inside the waveguide (e.g., at selected points) to simulate a much longer waveguide when in fact, it is not much longer?
6. If waveguide roughness is believed to be the chief' cause of losses, what positions or points on the cross-section arc most likely to contribute to losses? What can be done in advance around these points?
7. What would "applying a periodicity to the incoming laser light Pulse" do to our problem?
8. Could wc create a "periodicity in shape" to the waveguide, so that a unit length of it would represent 100 or more actual lengths? For example, what if the waveguide was extremely wavelike while it proceeds in its general direction? What if the amplitude of the physical wavelike waveguide was very high?
9. What action during the waveguide manufacture could reduce or eliminate waveguide roughness?
10. What would a pulsed laser beam do to this problem?
11. What would a pulse of different laser wavelengths do to this problem?
12. Can one part (operation) of' the waveguide be used primarily for transmission, and another part (operation) to reduce losses? If so, how so?
13. What would a "waveguide wound upon itself" mean, or look like, or do to this problem?
14. What if the variability of mean radius of the spiral waveguide were radically increased?
15. Can wc make a "waveguide within a waveguide?" Can wc carry this to extremes? What arc the implications?

COPYING PRINCIPLE #26

16. Make a list of what factors (materials, size, shape, configuration, etc..) might cause optical losses, and accentuate these factors in several simulated phase shift tests, using Taguchi Analysis to determine the "optimum" overall combination of parameters which has the least losses.
17. Consider ways to amplify the rotational effect on light transmission, making for an apparently larger rotational speed than actually exists (i.e., amplifying the Sagnac Effect).
18. Spiral the spiral (i.e., a spiral within a spiral).
19. Is the Sagnac Effect amplified by an electromagnetic field?
20. Is the Sagnac Effect amplified in combination with other effects?
21. Study standard rotational situations and compare actual versus standards.
22. Is there any relationship between the "optical losses" encountered, and rate of rotation? If so, could this be considered in developing the measuring system?
23. What if wc changed the 'TYPE' of electromagnetic radiation from the visible light range to, e.g., ultraviolet? infrared? wavelengths far beyond the visible range? Can phase shifts bc detected more easily'?

INTERMEDIARY PRINCIPLE #24

24. Can the laser light be re-circulated several (many'?) times within the waveguide to simulate the length of waveguide which normally would be required to yield high sensitivity?
25. Can additional light beams be introduced into the system to "protect" the phase-changed light from being lost due to waveguide roughness?
26. What intermediate substance (radiation?) can be applied between the incoming light and the rough areas of the waveguide, to act as a "buffer" zone, preventing or reducing losses?
27. Any intermediate layer or buffer zone will "smooth" out losses.

28. What third substance (electromagnetic radiation?) can be added to the system to reduce 10 SSCS?

29. Can the incoming light pulse be 'doctored" or "doped" in some way (e.g., with other light pulses) to make it less susceptible to losses, or on the other hand, to make the phase change more pronounced?

30. Can the incoming light be controlled by an electromagnetic (or other) field, in order to reduce losses during rotational measurements?

31. Explore means of making the waveguide more an-isotropic, promoting light transport along the length, but not radially.

32. Add a third (and fourth) effect to the Sagnac "Rotation-phase change" effect. Consider electromagnetism.

CHANGE OF COLOR PRINCIPLE #32

33. During fabrication of the waveguide, change color of the two different glass media in such a way as to reduce losses (e.g., change degree of reflectivity, etc.)

34. Coat waveguide with non-transparent medium during fabrication.

35. Form a waveguide cross- section which focuses any radial light inwards, thereby reducing losses because of the geometry of the waveguide's cross-section.

36. In general, make the waveguide more transparent to light along its length, and less transparent radially.

SELF-SERVICE PRINCIPLE #25

37. When the waveguide transmits light it uses the effect itself (light transmission and/or rotation) to reduce losses, or to improve sensitivity. Consider how this might be accomplished.

38. Coil several waveguides together lengthwise. Group several waveguides in parallel. Coil the waveguide to form a layer, then a next layer, etc., to simulate length. What will these three situations create?

39. Use the centrifugal force generated by rotation to change the density, and therefore, transmission properties (and losses??) of the waveguide. Is there a density/rotational relationship?

CHANGE OF MECHANICAL DESIGN PRINCIPLE #28

40. Introduce ferromagnetic particles into the waveguide material and change the phenomena with an electromagnetic field.

41. Use ferromagnetic particle additives to waveguide material to fabricate waveguide in the manner desired.

IX. Analysis of IORS Using Inventive Machine Prediction Expert System

By using Invention Machine Prediction (IM-Pr) Expert System a number of additional 22 new possible solutions and concepts were generated. The IM-Pr "Object1 - Action - Object2" interaction evaluation, as well as. the "Prediction Tree" analyses were explored. Some of these IM-Pr suggested solutions are similar to ones above resulted from the IM-P proposed solutions. Nevertheless, all of the IM-Pr suggested solutions are listed. The following are the IM-Pr suggested solutions:

1. Usc IORS with better efficiency by using on intermediate carrier article or intermediate process. Principle 24 - 'INTERMEDIARY':
   - Use of an intermediate carrier article or intermediate process
   - Merge one object temporary with another (which can be easily removed)
2. Use IORS with better efficiency by changing the transparency or color. Principle 32 - 'COLOR CHANGES':
   - Change of color of an object or its external environment
   - Change of transparency of' an object or its external environment
3. Use 10RS with better efficiency by replacing a mechanical means by electrical, magnetic or electromagnetic field. Principle 28 - MECHANICS SUBSTITUTION':
   . Replace a mechanical means with a sensory (optical, acoustic., taste or smell) means
   . Use electric, magnetic, and electromagnetic fields to interact with the object
   . Change from static to movable fields
   . From unstructured fields to those having structure
   - Use fields in conjunction with field- activated (e. g. ferromagnetic particles)
4. Use IORS with better efficiency by making each part of an object function in conditions most suitable for its operation. Principle 3'),( )('Al. QUALITY':
   - Change an object structure from uniform to non-uniform
   - Change an external environment (or external influence) from uniform to non-uniform
   . Make each part of an object function in conditions most suitable for its operation
   . Make each part of an object fulfill a different and useful function
5. Obtain IORS better efficiency by dividing an object into independent parts. Principle 1 - 'SEGMENTATION':
   - Divide an object into independent parts
   - Make an object easy to disassemble
   - Increase the degree Of fragmentation (segmentation of an object)
6. Obtain IORS with better efficiency by separating (in space or time) an 'interfering' part from an object. Principle 2 - 'TAKING (){11" :
   . Separate an 'interfering' part (or property) from an object or single out the only necessary part (or property) of an object
7. Obtain IORS with better efficiency by performing required changes of an object before it is needed. Principle 10- 'PRELIMANARY ACTION':
   - Perform, before it is needed, 11 the required change of an object (either fully or partially)
   .]'rearrange objects such that they can come into action from the most convenient place and without losing time for their delivery
8. Obtain IORS with better efficiency by using gas or liquid parts of an object instead of solid parts. Principle 29- 'PNEUMATIC & HYDRAULICS'
   - Use gas and liquid parts of an object instead of solid parts (e.g., inflatable, filled with liquids, air cushion, hydrostatic, hydro-reactive)
9. Obtain IORS with better efficiency by causing an object to vibrate or oscillate. Principle 18- 'MECHANICAL VIBRATION':
   - Cause an object to oscillate or vibrate
   - Increase its frequency (even up to ultrasonic)
   - Use an object's resonance frequency

- Use electric vibrators instead of mechanical ones
- Use combined ultrasonic and electromagnetic field oscillations

10. Weaken (reduce) action refraction, introduce additive with sharp memory effect into waveguide and/or cladding fabrication process.
11. Improve waveguide reflection by changing from uniform to composite materials. Principle 40: " USE OF COMPOSITE MATERIALS :
    - Composite materials (change from uniform to composite, multiple, materials)
12. Improve waveguide reflection by trying to achieve slightly more or lightly less of desired change of an object. Principle 16- 'PARTIAL OR EXCESSIVE ACTION':
    . If 100% Of an effect is hard to achieve using a certain solution method, then by using slightly less or slightly more of the same method, the problem may be considerably easier to Solve
13. Improve waveguide reflection by making portions of an object that have fulfilled their function go away. Principle 34 - 'DISCARDING AND RECOVERING':
    . Make portions of an object that have fulfilled their function go away (discard by dissolving, evaporating, etc.) or modify these directly during operation
    . Conversely, restore consumable parts of an object directly during operations
14. Improve waveguide reflection by making an object perform multiple functions. Principle 6- 'UNIVERSALITY':
    . Make a part of an object perform multiple functions; eliminate the need for other parts
15. Improve waveguide reflection by placing one object inside another. Principle 7- 'NESTED DOLL':
    - Place one object inside another, place each object in turn, inside the other
    - Make one part pass through a cavity in the other
16. Improve waveguide reflection by using harmful factors to achieve a positive effect. Principle 22 -'BLESSING IN DISGUISE':
    . Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect
    - Eliminate the primary harmful action by adding it to another harmful action to resolve the problem
    . Amplify a harmful factor to such degree that is no longer harmful.
17. Improve light loss by inverting the actions uses to solve the. problem (e.g. instead of cooling an object, heat it). Principle 13 -'THE OTHER WAY AROUND':
    - Invert the action(s) used to solve the problem
    . Make movable parts fixed and fixed parts movable
    - Turn the object "upside down"
18. Improve light loss by thermal expansion Principle 37 - "THERMAL EXPANSION':
    - Use thermal expansion (or contradiction) of materials.

19. Improve waveguide reflection by using pulsing actions or by per forming different actions between impulses. Principle 19. 'PERIODIC ACTION':
    - Instead of continuous action, use periodic or pulsing actions
    . If an action is already periodic, change the periodic magnitude or frequency
    . Use pauses between impulses to perform a different action

20. Improve waveguide reflection by using phase transition phenomena (e.g. volume changes, heal absorption). Principle 36 - ')'1 IASI TRANSITION':
   - Use phenomena occurring during phase transition (e.g. volume changes, loss of absorption of heat, etc.)
21. Improve waveguide reflection by using flexible shells and thin films. Principle 30 - 'FLEXIBLE SHELLS AND THIN FILMS'
   - Use flexible shells and thin films instead of three dimensional structures
   - . Isolate the object from the external environment by using flexible shells and thin film
22. Improve waveguide reflection by replacing normal environment with an inert one. Principle 39 - 'INERT ATMOSPHERE':
   - Replace a norms] environment with an inert one
   - Add neutral parts or inert additives to an object

X. Analysis of IORS Using Inventive Machine Effects Expert System

The Inventive Machine Effects (IM-E) Expert System was used to act as a refresher of knowledge related to physical, chemical and mechanical effects, that could be taken advantage of during the process of IORS innovative performance improvement. since polarization of input light is one effect that was needed to be considered, two light effects were searched for and provided as referenced information by the IM-E software. After the desired effect description, IM-11 software also provided suggestions to be followed. The two light effects listed by IM-E are:

1. Absorption of light

"Absorption of light is a decrease in the energy of a light wave propagation in a substance. This decrease is due to the transformation of the wave's energy into the intrinsic energy of the substance or the energy of secondary radiation that has another spectral composition and direction of propagation. The light absorption spectrum depends on the chemical nature and aggregate state of the substance. ']'1 ie color of dye and mineral solutions may be explained by selective light absorption. Absorption of light is used to study the composition of a substance, to make a chemical analysis of substance (absorption spectrum analysis). Infrared heaters are designed on the bases of electromagnetic wave absorption phenomenon".

The effect **absorption of light** allows the action EVALUATE WHERE LIGHT IS LOST AND CORRECT THE PROBLEM to be performed

Analysis of the solution achieved.

Implementation of solution obtained requires: INCREASE POLARIZATION OF INPUT LIGHT.

2. Double Refraction.

"Double refraction implies the splitting of a beam of light into two mutually perpendicular polarized beams that have different velocities of propagation in the medium, Double refraction occurs when the beam of light passes through an anisotropic transparent medium, The first beam is polarized perpendicularly to the optical axis of the crystal; the second beam is polarized in the principal plane of the crystal. The velocity of propagation and the refractive index of the first beam are independent of the direction of its propagation, while those of the second beam depend on its propagation. A phenomenon identical to double refr action can be observed in other wavelength ranges of magnetic waves",

The effect **double refraction** allows the action EVALUATE WHERE LIGHT IS 1,0S']' AND CORRECT ']'] HE PROBLEM to be performed.

Anal ysis of the solution achieved

Implementation of the solution achieved requires: INCREASED) 1'01 ,AR17,A'I'1ON OF INPUT LIGHT.

The two 1 M-ii effects listed above are both suggesting the same solution , which **s to increase polarization of input light.** This suggestion is added and counted as the 64-th M suggested possible solutions.

XI. Analogy Study, Evaluation and Selection of Best Solutions

For each of the 64 IM suggested solutions, IM data base also provided easy access and display of one or more examples of patents and inventions that are using similar principles as to the IM suggested solution. Through further analogy and personal expertise and experience, specific new proposed solutions to innovatively improve IORS angular rate sensing capability were generated. Most of these specific new proposed solutions were generated as a result of a trimming process and by combining two 01 more of the initial 64 1 M suggested solutions. Some of these new specific solutions had new conflicts and problems to be solved. For each of these new solutions, a "Course of Action" and "Expected Results>' were generated, along with the identification of "The Level of Practicality", 'Conclusion", and "Ranking". The header of the table used to evaluate and rank each specific new proposed IORS performance improvement solution is provided in Figure 3. In order to protect the newly generated IORS innovative improvement related intellectual property, the list of the new specific proposed solutions and their ranking are not shown.

'New Proposed Specific. Solution	New Problem or Conflict to be Solved	Level of Practicality	Conclusion	Final Ranking

Figure 3. Selection of Best New Specific Proposed Solutions

The first two ranked specific new proposed solutions were generated by combining two or more initial IM suggested possible solutions and were considered to have patent level of quality.